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Leptoquark Pair Production in $\gamma\gamma$ Scattering: Threshold Resummation[1]

Johannes Blümlein[a] and Alexander Kryukov[a,b]

[a] *Deutsches Elektronen-Synchrotron, DESY*
Platanenallee 6, D-15738 Zeuthen, Germany

[b] *Institute of Nuclear Physics,*
Moscow State University, RU–119899 Moscow, Russia

Abstract

The possibilities to pair–produce leptoquarks in photon–photon collisions are discussed. QCD threshold corrections lead to a strong enhancement of the production cross section. Suitably long–lived leptoquarks ($\Gamma_\Phi \lesssim 100\text{MeV}$) may form Leptoquarkonium states.

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Abstract: The possibilities to pair-produce leptoquarks in photon–photon collisions are discussed. QCD threshold corrections lead to a strong enhancement of the production cross section. Suitably long–lived leptoquarks ($\Gamma_\Phi \lesssim 100$MeV) may form Leptoquarkonium states.

Leptoquarks are hypothetical particles which combine quantum numbers of the fundamental fermions of the Standard Model and emerge as bosonic (scalar and vector) states in various extensions of the Standard Model such as unified theories and sub-structure models. In most of the scenarios the mass spectrum of these states is not predicted. In a series of models, however, one expects states in the range of several hundred GeV to a few TeV. These particles can be searched for at the next generation colliders as LHC and future e^+e^- linear colliders. Currently the following mass ranges are excluded by experiment for scalar leptoquarks:

$$\begin{array}{rcccl}
\text{1st generation leptoquarks} & : & M & > & 242 \text{ GeV [1] (CDF + D0)} \\
\text{2nd generation leptoquarks} & : & M & > & 202 \text{ GeV [2] (CDF)} \\
\text{2nd generation leptoquarks} & : & M & > & 200 \text{ GeV [3] (D0)} \\
\text{3rd generation leptoquarks} & : & M & > & 99 \text{ GeV [4] (CDF)} \\
\text{3rd generation leptoquarks} & : & M & > & 94 \text{ GeV [5] (D0)}
\end{array}$$

at 95 % CL irrespective of the size of the fermion–leptoquark couplings, which is limited to very small values [6, 7] for most of the leptoquark species. Somewhat higher bounds are derived for vector leptoquark states, depending on the size of their anomalous couplings to the gluon [8]. Unlike the fermionic couplings the couplings of the leptoquarks to the gauge bosons of the Standard Model are known, cf. [9], and are of the size of the standard gauge couplings of the fermions. Due to the smallness of the fermionic couplings leptoquark pair production processes at high energy colliders [2] allow to perform a widely model independent search for these states.

At e^+e^- high energy linear colliders the largest production cross sections are obtained for e^+e^- annihilation. This process was studied in detail in Refs. [9, 14] both for scalar and vector leptoquark states. The QED radiative corrections to scalar leptoquark pair production were calculated at $O(\alpha \log(s/m_e^2), O((\alpha \log(s/m_e^2))^2)$ both for initial and final state radiation as well as the $O(\alpha_s)$ QCD correction and the correction due to beamstrahlung in Ref. [16]. These

[2]This applies to high energy pp [8, 10, 11], ep [12, 8, 11], γe [8], $\gamma\gamma$ [13, 8] and e^+e^- [9, 14, 13, 15] collisions.

corrections are large in the threshold range. The enhancement due to the QCD corrections, being dominated by the Coulomb singularity $\propto 1/\beta$ at low velocities is nearly balanced by the losses due to the QED corrections and beamstrahlung despite of the smaller size of the QED coupling constant. The second order QED corrections are still of the size of $O(10\%)$ of the Born cross section and have therefore to be taken into account.

A second important production channel is photon–photon pair production of leptoquarks. Here we consider the case that the photon beams are produced form the electron and positron–beams, respectively, by Laser beam Compton back–scattering. The photon energy spectrum [17] is described by

$$\Phi_\gamma(z) = \frac{1}{N(x)}\left[1 - z + \frac{1}{1-z} - \frac{4z}{x(1-z)} + \frac{4z^2}{x^2(1-z)^2}\right] \quad (1)$$

$$N(x) = \frac{16+32x+18x^2+x^3}{2x(1+x)^2} + \frac{x^2-4x-8}{x^2}\log(1+x)\ , \quad (2)$$

where z denotes the longitudinal momentum fraction of the photons after beam conversion and $x = 2(\sqrt{2}+1)$, with $z \leq x/(1+x)$. Alternatively, one may consider leptoquark pair production by photon–photon scattering preparing the initial state through Weizsäcker–Williams emission from the e^+e^- beams. These contributions are, however, much smaller than those due to Compton–conversion, cf. [13, 8]. The photon–photon cross section reads

$$\sigma_{\Phi\overline{\Phi}}(s) = \int_0^{z_{max}} dz_1 \int_0^{z_{max}} dz_2 \Phi_\gamma(z_1)\Phi_\gamma(z_2)\ \hat{\sigma}_{\Phi\overline{\Phi}}(z_1 z_2 s)\ \theta(z_1 z_2 s - 4M_\Phi^2)\ . \quad (3)$$

For scalar leptoquarks the direct contribution to the sub–system cross section is given by

$$\hat{\sigma}_{\Phi_S\overline{\Phi}_S}(s) = \frac{\pi\alpha^2}{s} Q_\Phi^4 \left[2(2-\beta^2)\beta - (1-\beta^4)\log\left|\frac{1+\beta}{1-\beta}\right|\right]\ . \quad (4)$$

The corresponding relations for vector leptoquarks were derived in [13] and are somewhat lengthly due to the emergence of anomalous couplings.

Besides the direct contributions $\gamma\gamma \rightarrow \Phi\overline{\Phi}$ direct–resolved and resolved–resolved terms are present,

$$\sigma(\gamma+\gamma \rightarrow \Phi\overline{\Phi}) = \sigma_{dir.} + \sigma_{res.,dir.} + \sigma_{res.} \quad (5)$$

The latter ones are hadronic contributions and were calculated for both scalar and vector leptoquarks in Refs. [12, 13, 8] including two anomalous couplings for vector leptoquarks. The numerical analysis shows, that these terms contribute significantly only far away from threshold, i.e. typically for larger values of the cms velocities $\beta \geq 0.8$ of the leptoquarks [8].

In the search region (threshold) the photo–pair production cross sections behave like $\propto Q_\Phi^4$ and may vary by a factor of 625 between the production cross sections for $|Q_\Phi| = 1/3$ and for $|Q_\Phi| = 5/3$ states, which have the same cross section at a hadron collider. For vector leptoquark the cross sections are strongly sensitive to the anomalous couplings κ_γ and λ_γ [13, 8].

In the threshold region QCD corrections to the photon–photon process, similar as in e^+e^- annihilation [16], are very important. These corrections can only be calculated for the case of scalar leptoquark pair production, since for vector leptoquarks the effective Lagrangian does not correspond to a renormalizable theory. We will therefore limit the consideration to the case of

scalar leptoquarks here. Threshold resummations of the universal terms have been considered in the literature before, cf. Refs. [18, 19, 20]. For a final state of a pair of scalar leptoquarks we follow [21]. The Born cross section $d\sigma_B$ obtains the correction factor $K_S(E)/K_S^{(B)}(E)$,

$$d\sigma = d\sigma^{\rm BORN} \frac{K_s(E)}{K_S^B(E)} \tag{6}$$

$$\begin{aligned} K^{(B)}(E) &= \frac{M_\Phi}{4\pi}\sqrt{M_\phi E} && (7)\\ K_S(E) &= \frac{M_\Phi^2}{4\pi}\left\{\frac{k_+}{M_\Phi} + \frac{2k_1}{M_\Phi}\arctan\left(\frac{k_+}{k_-}\right)\right.\\ &\left. + \sum_{n=1}^{\infty}\frac{2k_1^2}{M_\Phi^2 n^4}\frac{\Gamma_\Phi k_1 n + k_+\left[n^2\sqrt{E^2+\Gamma_\Phi^2}+k_1^2/M_\Phi\right]}{\left[E+k_1^2/(M_\Phi n^2)\right]^2+\Gamma_\Phi^2}\right\}, && (8) \end{aligned}$$

with $E = \sqrt{s} - 2M_\Phi$. M_S and Γ_S denote the mass and width of the scalar leptoquark and

$$\begin{aligned} k_1 &= \frac{2}{3}\alpha_s(M_\Phi)M_\Phi \\ k_\pm &= \sqrt{\frac{M_\Phi}{2}\left(\sqrt{E^2+\Gamma_\Phi^2} \pm E\right)}\,. \end{aligned}$$

Here the strong coupling constant $\alpha_s = \alpha_s(M_S^2)$ was considered to be fixed.

In Figure 1 the ratio of the integrated cross section with threshold resummation and the Born cross section is shown assuming a decay width of $\Gamma_S = 1$GeV as an illustration. [3] Threshold enhancements of a factor 5–8 can be obtained.

If the width of the leptoquarks turns out to be $\lesssim 100$ MeV *Leptoquarkonia* can be formed in $\gamma\gamma$–collisions, cf. [16] [4]. The β–behavior at threshold is favoring the $\gamma\gamma$–process ($\sigma \propto \beta$) in comparison to the e^+e^- process ($\sigma \propto \beta^3$). In Figure 2 the total cross sections are shown with and without threshold resummation.

To summarize, photon pair–production of scalar and vector leptoquarks at future e^+e^- linear colliders were studied. The cross sections vary by the leptoquark charge as $|Q_\Phi|^4$, which may mean a variation up to a factor of 625. This production process offers a background free window to study the anomalous couplings κ_A and λ_A of potential vector leptoquark states to the photon. The threshold QCD enhancement of the photon–photon process is of $O(5-8)$ for typical choices of the parameters. Leptoquarkonia can be formed in the photon–photon process iff their width is $\Gamma_\Phi \lesssim 100$MeV.

References

[1] CDF and D0 collaboration, FERMILAB-PUB-98/312-E.

[3] The 'idealized' decay widths are by far smaller due to the the small fermionic couplings. However, the real leptoquark width should be larger since these particles are supposed to fragment into hadrons similar as quarks do. A theoretically safe value of the width is hard to obtain due to these non–perturbative effects.

[4] This possibility was later discussed in [22, 23] too.

[2] F. Abe et. al, CDF collaboration, Phys. Rev. Lett. **78** (1997) 2906.

[3] B. Abbott et. al, D0 collaboration, FERMILAB-PUB-99/314-E and `hep-ex/9910049`.

[4] F. Abe et. al, CDF collaboration, Phys. Rev. Lett. **81** (1998) 4806.

[5] B. Abbott et. al, D0 collaboration, Phys. Rev. Lett. **81** (1998) 38.

[6] A.F. Zarnecki, `hep-ph/0006196`.

[7] S. Davidson, D. Bailey, and B.A. Campbell, Z. Phys. **C61** (1994) 613.

[8] J. Blümlein, E. Boos, and A. Kryukov, Z. Phys. **C76** (1997) 137.

[9] J. Blümlein and R. Rückl, Phys. Lett. **B304** (1993) 337.

[10] J. Blümlein, E. Boos, and A. Kryukov, DESY 97–067, `hep-ph/9811271`.

[11] J. Blümlein, Z. Phys. **C74** (1997) 605.

[12] J. Blümlein, E. Boos, and A. Kryukov, Mod. Phys. Lett. **A9** (1994) 3007.

[13] J. Blümlein and E. Boos, Nucl. Phys. Proc. Suppl. **37B** (1994) 181.

[14] J. Blümlein, E. Boos, and A. Kryukov, Phys. Lett. **B392** (1997) 105.

[15] J. Blümlein and P. Frampton, IFP-475-UNC and in Proceedings of the 2nd Int. Workshop on Physics with Linear e^+e^- Colliders, Waikoloa, HI, 26–30 April 1993 (World Scientific, Singapore, 1993) p. 926.
F. Cuypers, P. Frampton, and R. Rückl, Phys. Lett. **B390** (1997) 221.

[16] J. Blümlein, DESY 93–132, Proceedings of the 2nd Int. Workshop on Physics and Experiments with Linear e^+e^- Colliders, Waikoloa,HI, 26–30 April 1999, p. 542;
J. Blümlein, DESY 93–153, Proceedings of the Linear Collider Workshop 1993, p. 419.

[17] I.F. Ginzburg, G.L. Kotkin, V.G. Serbo, and V.I. Telnov, Nucl. Instr. Meth. **205** (1983) 47.

[18] V.S. Fadin and V.A. Khoze, JETP Lett. **46** (1987) 525; Sov. J. Nucl. Phys. **48** (1988) 309.

[19] I.I. Bigi, V.S. Fadin and V.A. Khoze, Nucl. Phys. **B377** (1992) 461.

[20] M.J. Strassler and M.E. Peskin, Phys. Rev. **D43** (1991) 1500.

[21] I.I. Bigi and F. Gabbiani, UND-HEP-91-BIG08.

[22] V.V. Kiselev, Phys. Atom. Nucl. **62** (1999) 300 and Phys. Rev. **D58** (1998) 054008.

[23] D. Browser–Chao, T. D. Imbo, B.A. King, and E.C. Martell, Phys. Lett. **B432** (1998) 167.

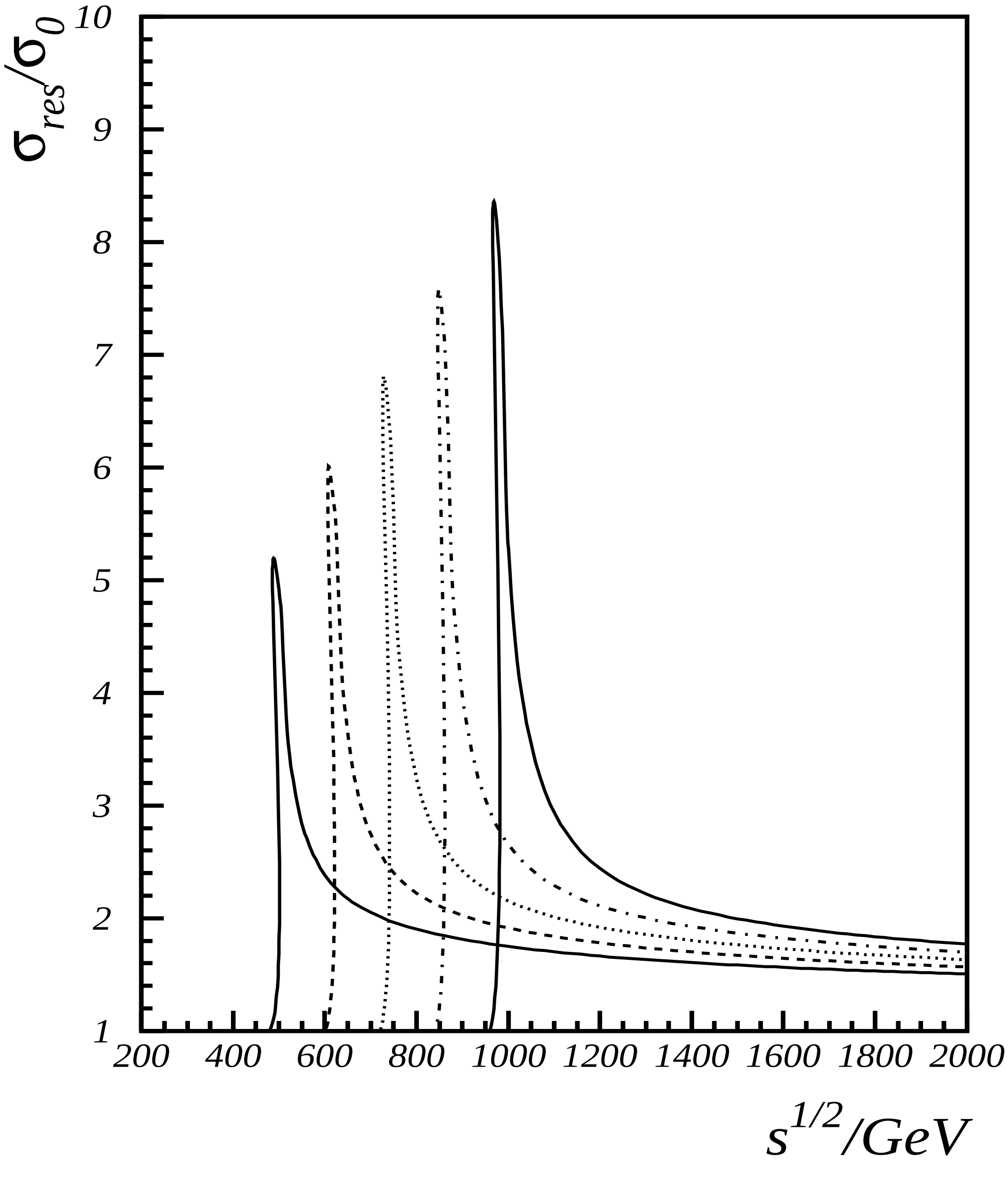

Figure 1: Ratio of the leptoquark pair production cross section including the threshold resummation and the Born cross section as a function of $\sqrt{s}$. Left full line: $M = 200$ GeV; dashed line: $M = 250$ GeV; dotted line: $M = 300$ GeV, dash–dotted line: $M = 350$ GeV; right full line: $M = 400$ GeV.

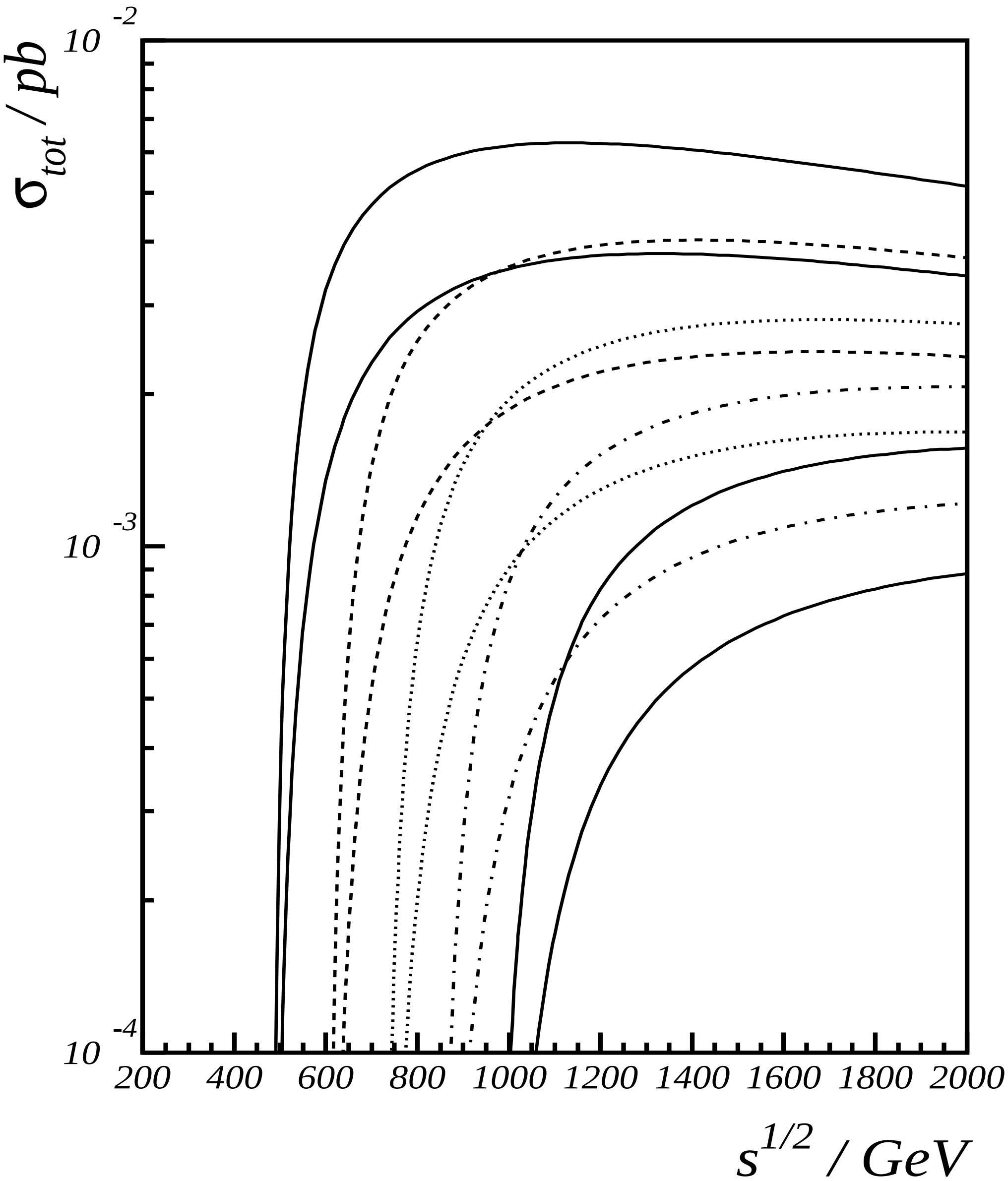

Figure 2: Leptoquark pair production cross section $\sigma(\gamma\gamma \rightarrow \overline{\Phi}\Phi)$ as a function of $\sqrt{s}$. Each pair of equally drawn lines corresponds to the same leptoquark mass. Upper line: $\sigma^{\rm Born} + \sigma_{resum}$; lower line: $\sigma^{\rm Born}$. Upper full lines: $M = 200$ GeV; dashed lines: $M = 250$ GeV; dotted lines: $M = 300$ GeV, dash–dotted lines: $M = 350$ GeV; lower full lines: $M = 400$ GeV.